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## Gait Versatility Through Morphological Changes in a New Quadruped Robot

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**Abstract:** In dynamic locomotion, robots' morphology and the ability to adapt it online play an important role for energy efficiency and coping with the highly unpredictable perturbations from the environment. In this paper, we present the design and implementation of a quadruped robot, whose morphology is particularly targeted toward energy-efficient dynamic locomotion. We propose a combination of mechanisms, which allows for gait versatility, energy-efficient actuation and ground clearance through adaptation of morphology (i.e., morphosis). We report on a series of experiments to validate the robot's performance in different locomotion conditions.

**Keywords:** robot design, legged locomotion, morphological computation, gait versatility, energy efficiency, morphosis

### 1. INTRODUCTION

Biological systems show amazing locomotion capabilities. The combination of their morphology (musculoskeletal structure, body shape, etc.) and sensory-motor control allows them to traverse diverse terrains and to switch among gaits to maintain varying levels of speed at optimized energy efficiency. With the goal to match these impressive capabilities, roboticists have put vast efforts to derive inspiration from biology and transfer it into the design of robots' morphology [1]. We have identified the following key factors that need to be addressed in a dynamic legged robot:

- **Power:** In dynamical running, the robot has to deliver a large amount of energy within a fraction of a second in order to jump off.
- **Compliance:** For energy storage and instant adaptation to external forces, compliant structures have to be integrated into the robot's legs.
- **Ground clearance.** When legs are propagated forward during a swing phase, they need to clear the ground.
- **Gait versatility:** Legged animals are able to locomote in different gaits, mostly, in order to adapt to new terrain or to change speed, at minimized cost of transport [2]. Therefore, it is crucial for an agile robot to be able to exhibit different gaits.

To integrate all these, sometimes competing requirements, into a single design is a challenge. For instance, high power-to-weight ratio conflicts with controllability and gait versatility. Specifically used as inspirations in our work are the iSprawl [3] and Scout II [4] robots. The iSprawl robot demonstrates fast and robust dynamic hexapedal locomotion, due to carefully designed compliant properties and the fast and efficient prismatic joint actuations. The Scout II quadruped robot shows several fast and robust running gaits (i.e., trot, bound, and gallop), but only with one rotational degree-of-freedom per leg and linear compliance.

We present a novel solution to address the previous listed key factors: the quadruped robot UZH1 (Fig. 1). High power-to-weight ratio was achieved by using only one motor for locomotion per leg. The motors were placed towards the center of mass in order to minimize counter-forces and inertial moments. In addition, the

motors rotate continuously providing energy-efficient output since they do not "fight" against their own inertia (which is the case as oscillating). The oscillatory movement of the leg is then achieved through a crank-slider mechanism.

The additional design requirements were fulfilled in the following manner: First, compliance was introduced by incorporating springs within the leg structure. Second, ground clearance was already incorporated into the crank-slider mechanism, obtaining an oval foot trajectory. With this adopted mechanism, while we gain a two-dimensional foot trajectory with only one motor per leg, these trajectories are fixed and not controllable. Therefore, third and last, we introduced the missing flexibility that is needed for different gaits through mechanisms that allow the robot to change its leg configuration - which we call *morphosis*. The ground clearance profile (GCP) can be adjusted online (through additional lightweight "morphosis motors") and offline. With the morphosis capabilities our work goes beyond that of K. Iida[5].

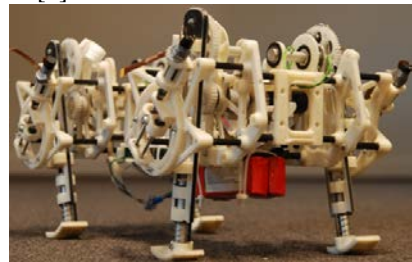


Fig.1 UZH1 Robot Prototype; overall dimension: (LxWxH: 350, 250x200 [mm]); weight: 2.25kg.

The paper is organized as follows, we begin by presenting the design concept and implementation details of the UZH1 robot. We then describe a series of experiments designed to evaluate the robot's performance.

### 2. DESIGN AND IMPLEMENTATION

As shown in Fig.2, each leg of the UZH1 robot has two degree of freedoms: a prismatic and a rotary joint. The first one is a passive compliant joint allowing for energy storage and impact absorption. The second one is controlled by the continuous rotation of a crank disk

mounted at the end point of the leg. The leg is constrained by one end point mounted on the crank disk and the slider rotating about the fix point. As a result, the foot produces a GCP as shown in Fig.2 (d).

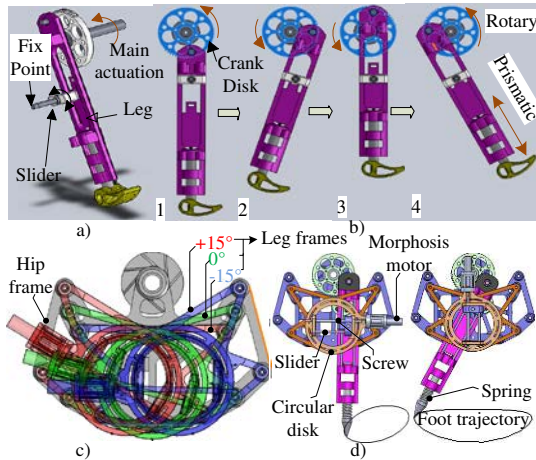


Fig.2 Operational principle of the robot's leg design; (a) main components of the robot leg; (b) from (1)-(4): leg movement in one working cycle; (c-d) online and offline morphosis possibilities influencing the foot trajectory.

In order to provide diverse locomotion capabilities, we introduce two levels of morphosis: online and offline. In the online morphosis, we vary the fix point position in order to provide possibilities to change leg configuration. As shown in Fig.2, the position of the fix point determines the trajectory of the end point of the robot's foot. By moving the fix point along with the screw via the morphosis motor, the foot trajectory, which depends on the offset angle and the oscillating amplitude, can be varied. The influence of the fix point movement on the changing ratio between the offset angle and the oscillating amplitude also depends on the orientation of the screw, shown in Fig. 2 (d).

In the offline morphosis, the circular disk, at which the screw is mounted on, can be rotated in a full circle with resolution of 5° on the leg frame allowing to vary the foot trajectory. Additionally, one can rotate the whole leg frame by 15° to either side. As a result, this creates a larger change of the offset angle, shown in Fig. 2 (c).

### 3. EXPERIMENT: GAIT VERSATILITY

We investigated the robot's capabilities using a simple CPG architecture [6] without any sensory feedback. The main goal of the presented experiments is to gain insights to the abilities of the compliant, morphological structure of UZH1 in combination with this simple open-loop control.

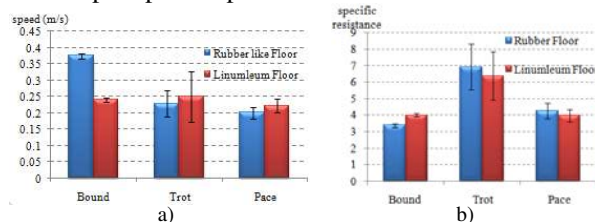


Fig.3 The robot speeds and specific resistances in different gaits on different floor materials.

In a series of experiments, we have jointly explored the space of control (speed, duty factor, phase difference), morphological parameters (slider orientations and fix point positions) and different terrains. These resulted in three different gaits, namely bound, trot, and pace. The highest speeds and the specific resistances are shown in Fig.3.

As a result, the morphological parameters such as the combination of different slider orientations and the fix points at the best speeds were thoroughly investigated through number of experiments as shown in the Fig.4.

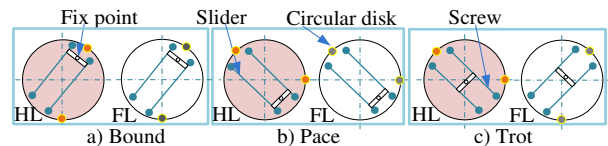


Fig.4 The different slider combinations in different gaits for the best speed; FL: front leg; HL: hind leg.

## 4. DISCUSSION, CONCLUSION, FUTURE WORK

We presented a novel robot design that aims at dynamic, energy-efficient, yet versatile locomotion. The missing active degrees of freedoms that were sacrificed for the sake of higher power-to-weight ratio were compensated by mechanisms that manipulate the robot's morphology. We have successfully demonstrated the robot's performance in multiple gaits and multiple grounds, with a simple feed-forward controller. We speculate that the robustness that we observed was due to self-stabilization properties of the compliant mechanical structure.

The current level of the energy-efficiency is shown in Fig.3b. We plan to investigate how to improve it with closed-loop control using touch sensors at the feet in order to achieve proper footfalls. In addition, we will compare rotary with oscillatory movement regarding energy consumption of the main actuators as future work.

## 5. ACKNOWLEDGEMENT

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